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Surface Wave Suppression with Joint S Transform and TT Transform

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Abstract

The TT transform (Time-Time transform) is a new method to process non-stationary signal based on S transform, has a good ability of frequency conversion. The surface wave, with lower frequency compare with other seismic wave, can be suppressed through extracting the TT spectrum's diagonal elements of seismic data. However, this method has a deficiency that in pressing low-frequency signal, retaining a part of high-frequency interference that can be eliminated. But, the high-frequency interference can be removed by the S transform filtering. Therefore, a method of joint the S transform and TT transform to suppress surface wave is presented. Firstly, apply S transform time-frequency filtering for each trace seismic data to suppress the high frequency interference and random noise, and then, use TT filtering to suppress the surface wave with low frequency.

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Keywords: S transform；Time-Time transform；Time-frequency filtering；joint suppression；seismic surface wave

1. Introduction

The S transform [1] is a kind of new spectrum decomposition method that developed in last ten years. It provides a representation of a one-dimensional time series into a two-dimensional time–frequency map of time-local spectral information. The S transform has been widely used in many areas such as marine, mechanical engineering, seismic exploration, medical, upper atmospheric physics and so on.

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Pinnegar proposed TT transform in 2001, that was a new two-dimensional time–time representation of a one-dimensional time series based on the S transform [2]. TT transform has a similarity with the S time.

S transform is both of them can obtain the two-dimensional local time properties of the one-dimensional time signal through the scaled windows. However, there is difference of them, the S-transform transforms one-dimensional time signal to the two-dimensional time-frequency domain while the TT-transform transforms one-dimensional time signal to two-dimensional time-time domain. According to the distribution characteristics of the in time-time domain, the signal can be processed. Pinnegar et al (2005) processed non-stationary signal time varying filtering using the TT transform [3, 4], Fan X (2009) detected mechanical fault with TT transform [5], and Jianqing M (2011) applied the TT transform to seismic surface wave suppression [6], have achieved good effects. In generally, we are most interested in the diagonal elements of the TT transform spectrum in the actual application. So, Simon (2008) showed a very simple way of computing the diagonal part of the TT transform and to give a clear interpretation of it [7] that improved the calculation efficiency and practicality.

Surface wave is a kind of regular disturbing wave which has the characteristics of low-frequency, high amplitude, strong energy and so on in seismic reflection data. The effective reflection wave is often covered by the existence of surface wave, and then the signal-to-noise ratio of the reflection data is reduced. Therefore, the suppression of surface wave has a direct effect on the seismic data processing, even affects the migration imaging results, and ultimately affects the final geological interpretation. At present, there are many popular methods to suppress seismic surface wave, such as f-k transform [9], the Radon transform [10], S transform time-frequency filtering method [11], et al.

In This paper, we joint the advantages of the S transform and TT transform, apply them to the real seismic surface wave suppression based on the characteristics of the surface wave.

2. The S transform and the TT transform

Stockwell etc (1996) defined the S transform of a signal $h(t)$,

$$S(\tau, f) = \int_{-\infty}^{+\infty} h(t)w(t-\tau, f)\exp(-i2\pi ft)dt \tag{1}$$

Where, $S(t, f)$ indicates that the signal S-transform, $w(t, f) = |f| / k\sqrt{2\pi}e^{(-f^2t^2/2k^2)}$, ($k > 0$) is the Gauss window function, τ is the center of the window function.

Taking the inverse Fourier transform of both sides of (1) yields

$$TT(t, \tau) = \int_{-\infty}^{+\infty} S(t, f)\exp(+i2\pi f\tau)df \tag{2}$$

If for a specific t , considering all the τ, the result of (2) is a time-local function. The scaling properties of the S-transform lead to higher amplitudes of high frequencies (as compared to low frequencies) around $\tau = t$.

Because of

$$\int_{-\infty}^{+\infty} TT(t, \tau)dt = h(\tau) \tag{3}$$

Therefore, like the S transform, the TT-transform is also completely invertible.

Inserting (1) and Gauss window function into (2), we can rewrite the TT-transform as

$$TT(t,\tau)=\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}|f|/k\sqrt{2\pi}\,h(\theta)\times e^{-(f^2(\theta-\tau)^2/2k^2)}e^{-i2\pi f(\theta-t)}d\theta\, df \tag{4}$$

For a continuous signal *h*, through interchanging the order of integration. we can get

$$TT(t,\tau)=\int_{-\infty}^{+\infty}h(\theta)g_k(\theta-t,\theta-\tau)d\theta \tag{5}$$

Where,

$$g_k(\tau,t)=\int_{-\infty}^{+\infty}|f|/k\sqrt{2\pi}e^{-(f^2\tau^2/2k^2)}e^{-i2\pi ft}df \tag{6}$$

this integral can be solved analytically and gives

$$g_k(t,\tau)=\begin{cases}\sqrt{\dfrac{2}{\pi}}\dfrac{k}{\tau^2}-2\pi k^2\dfrac{t}{\tau^3}e^{-2(\pi k(t/\tau))^2}Erfi(k\pi\sqrt{2}\dfrac{t}{\tau}),\forall\,\tau\neq 0\\ -\sqrt{\dfrac{2}{\pi}}\dfrac{1}{kt^2},\tau=0\end{cases} \tag{7}$$

Where $Erfi$ is the imaginary error function, we can set

$$p_k(x)=k\sqrt{2/\pi}-2\pi k^2xe^{-2(\pi kx)^2}Erfi(\sqrt{2}k\pi x) \tag{8}$$

Then,

$$g_k(t,\tau)=1/\tau^2p_k(t/\tau),\forall\,\tau\neq 0 \tag{9}$$

Therefore, for $t/\tau=1$,

$$TT(t,\tau=t)=p_k(1)\int_{-\infty}^{+\infty}h(\theta)\frac{1}{(\theta-\tau)^2}d\theta \tag{10}$$

Which is a convolution. According to the relation of convolution and product, we can calculate the TT-transform as the inverse Fourier transform of a product:

$$TT(t,t)=F^{-1}\{H(f)G(f)\} \tag{11}$$

Where $F\{\cdot\}$ represents the Fourier transform, $F^{-1}\{\cdot\}$ its inverse, H is the Fourier transform of the signal h, and G is the Fourier transform of the diagonal terms of g. using integral transform,

$$G(f)=F\{g(t,t)\}=-2p_k(1)\pi^2|f| \tag{12}$$

This equation shows that, in the valid frequency band range signal, G is proportional to $|f|$, the greater $|f|$, the greater the G, and the greater $TT(t,t)$, namely, the diagonal elements of the value of TT transform spectrum become more bigger. that is also the nature of the scaling properties of S lead to higher amplitudes of high frequencies (as compared to low frequencies) around $t = \tau$.

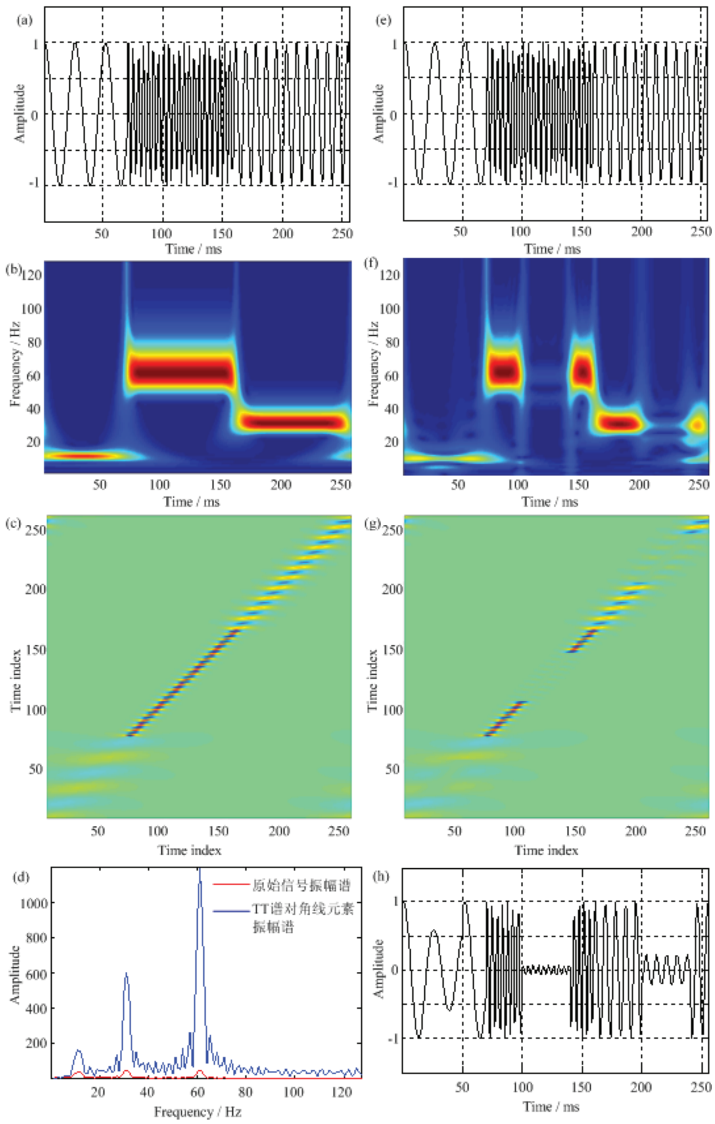

Fig.1. Time-varying filtering of synthetic signal with the S transform and TT transform. (a) A synthesized time series; (b) S transform spectrum of the time series (a); (c) TT transform spectrum of the time series (a); (d) Amplitude spectrum of the time series (a) and the diagonal elements in TT transform spectrum; (e) inverse TT transform; (f) S transform time-frequency filtering spectrogram; (g) TT transform Time-varying filtering spectrum; (h) the result of TT transform Time-varying filtering.

In order to elaborate the properties of the S transform and the TT transform, we analyse a model data using the S transform and the TT transform.Fig.1 (a) is an artificially synthesized signal composed of three cosine signal by frequency of 5Hz, 30Hz and 60Hz. Fig.1 (b) is the S transform spectrum, it has a good time-frequency resolution. The signal with the different frequency can be separated clearly. Fig.1 (c) is the TT transform spectrum, the wider the ribbon diagram, the lower the frequencies. The 1-70 sampling points is a low-frequency background for the synthesis signal, corresponding to the TT-transform spectrum of [1:70, 1:70], the diagonal position is a wide ribbon. The depth of color indicates that the size of the energy, the deeper color, the higher energy. So, in TT-transform spectrum, the energy in the diagonal positions is higher than the position away from the diagonal positions. Fig.1 (d) is the amplitude spectrum of the time series (a) and the diagonal elements in TT- transform spectrum. In this plot, we can see the TT-transform clearly emphasizes high frequencies at the cost of low frequencies.Fig.1 (e) is the inverse TT transform of the time series, which indicates the TT transform is reversible. Fig.1 (f)-(h) respectively is time-varying filtering with the S transform and the TT transform.

Through theoretical analysis and numerical simulation, we can summarize the basic properties of the S transform and the TT transform. The S transform inverse transform and Fourier transform is directly linked to ensure that it is the non-destructive transform; linear transform ensure there is no cross-terms; time-frequency resolution and the signal frequency-related; basic wavelet do not have to meet the permit conditions; scale makes the generalized S transform have good aggregation ability for frequency. TT transform is a non-destructive transform, and has good ability in gathering frequency; it gathers the high frequency signal in diagonal position of TT spectrum. Namely, the range of high frequency signal is narrower than low frequency signal's near the diagonal of TT spectrum; the amplitude is also higher. These properties of TT transform are the theoretical basis of its application in seismic data processing.

3. Application to real seismic data

Because of using the fast Fourier transform, the TT transform has a high efficiency in suppressing seismic surface wave. However, the TT transform also has a defect that when extracting high frequency signal and suppressing low frequency signal, meanwhile, it may miss a little of effective signal with lowfrequency and retain some interference with high frequency. In this case, the amplitude of record after surface wave suppression would be changed [6]. We can provide a time-domain signal into time-frequency map using the S transform. Then, design a time-frequency filter, fill zero in area of interfere signal, and finally apply the inverse S transform to the time domain. Above produces called the S transform time-frequency filtering. The S transform, with linear and reversible properties, it dose not make cross term and cause loss of information during transform signal from time domain and time-frequency domain. In this paper, we try to take advantage of the S transform and the TT transform to suppress the seismic surface wave. The basic procedure stated as following: Firstly, we perform time-frequency filtering for each trace seismic data using the S transform, to suppress the high frequency interference and random noise. Then, apply the TT transform filtering for all above treated seismic record to suppress surface wave with its good frequency gather ability through extracting the diagonal elements of near the TT spectrum.

Fig.2 (a) is a real seismic shot record, sampling interval for 4ms, 1,000 sampling points, and interval for 25m. From the real record, we can see that the surface wave near-offset is more developed, and is significant dispersion. Fig.2 (b) is the filtered record using joint the S transform and the TT-transform, it is clear to see that low-frequency surface wave has been effectively suppressed, while that of other seismic waves which the frequency are higher than the surface wave are still a clear reservation, in particular, the reflections axis buried in the surface wave record become more continuous. Fig.3 is the S-transform time-frequency spectrums of 55th trace before and after surface wave suppression. Similarly, in the time-frequency spectrum, the surface wave is completely suppressed (see the white box). Processing result shows that the joint the S transform and the TT-transform is very effective in surface wave suppression.

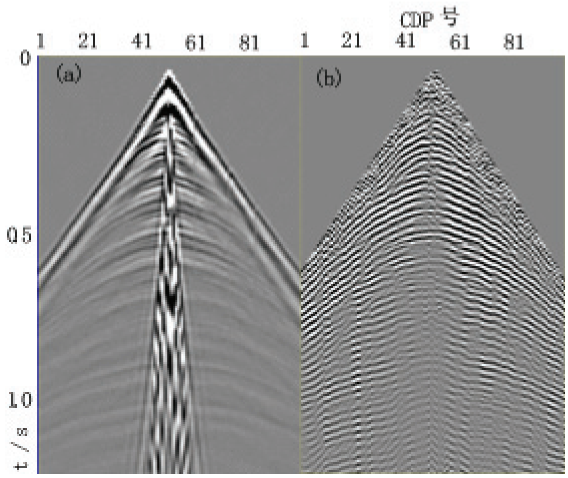

Fig.2. Surface wave suppressed by joint S and TT transform. (a) real seismic data record; (b) the record after suppression

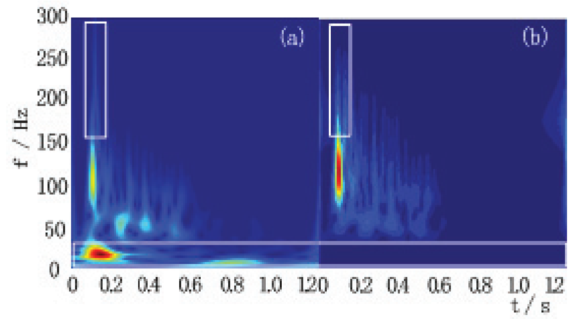

Fig.3. Time-frequency analysis of single trace in real seismic data. (a) Time-frequency spectrum of 55th trace of original record; (b) Time-frequency spectrum of 55th trace of after surface wave suppressed with joint S and TT transform

4. Conclusions

Through theoretical analysis and numerical simulation, as well as actual data processing, we can get the following conclusions:

(1) The TT transform is actually an extension of the S transform, and is closely linked with S transform; both of them are lossless reversible.

(2) The TT transform has good frequency gather ability. Near the diagonal of the TT-transform spectrum, gathering capacity of the high-frequency signal is stronger than the low-frequency signal, distribution is narrower, and amplitude is higher.

(3) Although the TT transform in the suppression of surface wave has a significant effect, a number of effective low-frequency signals are rejected during extracting high-frequency and suppressing low-frequency, the parts of the high frequency interference are retained, that is the deficiency of TT-transform.

(4) We proposed the method of joint the S transform and the TT transform can avoid. The illusion of interpretation and received an effective result in seismic surface wave.

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